Recent R_{AA} Results from the PHENIX Experiment

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Abstract. The nuclear modification factor R_{AA} has, for more than one decade, been one of the workhorse variables in the field of Ultra-relativistic Heavy Ion Collisions. It describes the deviations of the yield of a given probe, such as π^0 yields, as compared to the yield that would have been obtained from a simple-minded superposition of independent proton-proton collisions. In addition to new π^0 suppression results in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}= 200\,\mathrm{GeV}$, we present recent results from π^0 yields from the currently ongoing RHIC low energy scan, measurements of the jet fragmentation function in Cu+Cu, and the R_{AA} from fully reconstructed jets in Cu+Cu collisions.

1. The nuclear modification factor of Neutral Pions

The R_{AA} variable (1) is the ratio of the yield of a particle or probe obtained in heavy-ion collision and the yield obtained in p+p collisions, scaled to the equivalent number of binary collisions,

$$R_{\mathrm{AA}} = \frac{1/N_{evt} dN/dydp_T}{T_{AB}(b) d\sigma^{pp}/dydp_T} \tag{1}$$

σ^{pp} is the production cross section of the particle in p+p collisions, and T_{AB} is the nuclear thickness function calculated within a Glauber model [1].

The PHENIX apparatus [2] can reconstruct neutral pions from the decay photons measured in the electromagnetic calorimeter. Figure 1 shows the nuclear modification factor of neutral pions in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}= 200\,\mathrm{GeV}$ as a function of p_T. The data are shown for different centrality classes 0-10%, 30-40%, g50-60%, and 80-93%.

The control measurement of the nuclear modification factor in d+Au collisions, R_{dAu}, for $\sqrt{s_{\mathrm{NN}}}= 200\,\mathrm{GeV}$ [4] provides evidence that the observed hadron suppression in Au+Au collisions cannot be explained by initial state effects. The suppression is significantly smaller in d+Au collisions for the most central collisions, and there is a slight enhancement in peripheral collisions (Figure 2).

It is interesting to compare the results with the most recent Pb+Pb data at $\sqrt{s_{\mathrm{NN}}}= 2.76\,\mathrm{TeV}$ published by the ALICE collaboration, which has measured the nuclear

‡ A list of members of the PHENIX Collaboration can be found at the end of this issue.

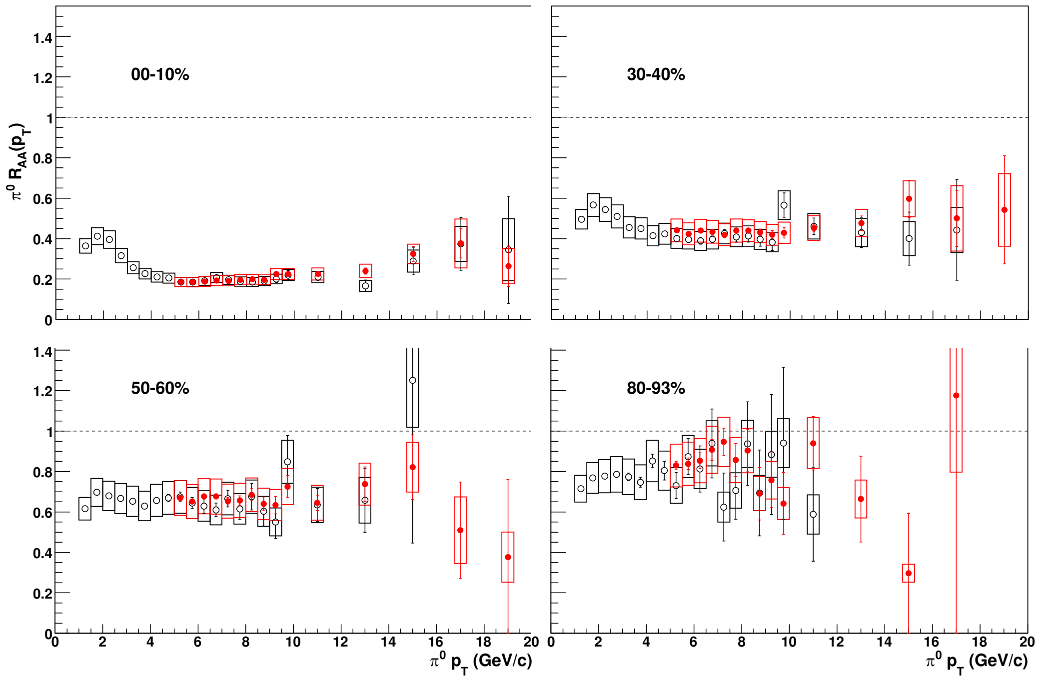

Figure 1. The nuclear modification factor of π^0 as a function of p_T for the most central (0-10%), medium (30-40% and 50-60%), and peripheral (80-93%) Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV. The black open circles are the published data [3] and the red circles are the recent preliminary data presented at the conference.

modification factor for charged hadrons in a 0–5% centrality range [5], similar to the PHENIX measurement. Figure 3 shows the comparison of PHENIX neutral pion data from the most central 0–5% class with the charged hadron R_{AA} as a function of p_T measured by the ALICE experiment [5]. The data show a very similar behavior. The slight upward trend in the ALICE data is compatible with the PHENIX data.

2. Participant Scaling

We can select the size of the collision system by varying the collision species and the collision centrality. The same number of participants in different systems should give a similar nuclear modification factor at the same energy ("participant scaling"). Figure 4 shows the nuclear modification factor of π^0 as a function of the number of participants N_{part} at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV for Au+Au and Cu+Cu for p_T above 7 GeV/c. The data show very similar behavior for the different systems.

3. The Search for the Transition from Enhancement to Suppression

The RHIC low energy scan is underway, which will allow us to pinpoint the transition from the enhancement of the hadron yields observed at SPS energies ($\sqrt{s_{\mathrm{NN}}}$= 17.3 GeV) to the suppression observed at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV for Au+Au at RHIC. Most recently, we have collected a dataset at $\sqrt{s_{\mathrm{NN}}}$= 19.6 GeV, although no results are available yet. We

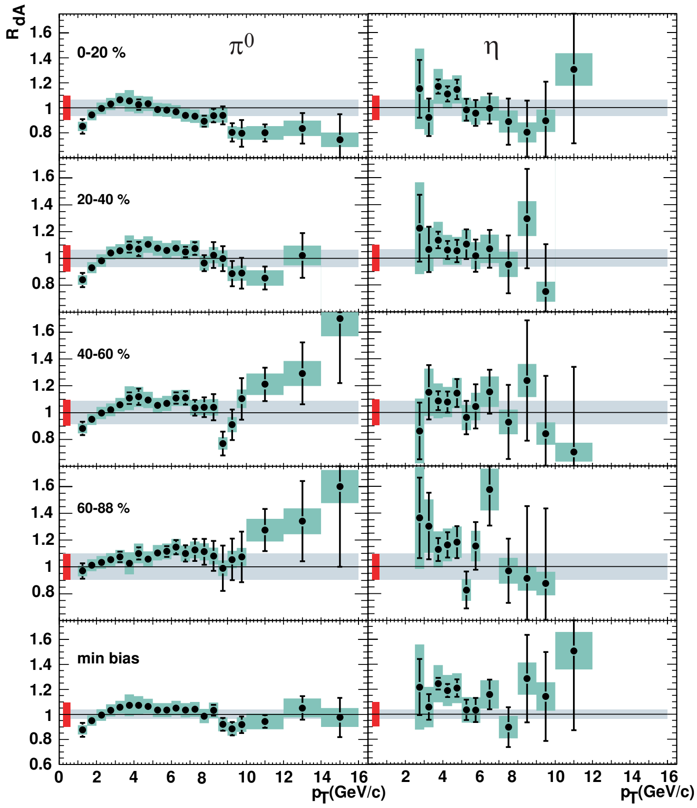

Figure 2. The nuclear modification factor of π^0 and η as a function of p_T for d+Au collisions at $\sqrt{s_{\mathrm{NN}}}=$ 200 GeV for various centralities. The data are compatible with a nuclear modification factor of 1 for the d+Au system, providing evidence that the observed hadron suppression in Au+Au collisions cannot be an initial-state state effect.

have so far analyzed datasets for Au+Au at $\sqrt{s_{\mathrm{NN}}}=$ 200, 130, 62.4, and 39 GeV, and for Cu+Cu at $\sqrt{s_{\mathrm{NN}}}=$ 200, 62.4, and 22.4 GeV [6].

So far, all of the analyzed Au+Au datasets exhibit the hadron suppression in central collisions, as seen in Figure 5. For the lowest energy $\sqrt{s_{\mathrm{NN}}}=$ 39 GeV, the nuclear modification factor shows an enhancement for the medium peripheral centrality (40–60%), while the most central data are still suppressed.

The only data point at RHIC which exhibits the enhancement in central collisions so far is the Cu+Cu system at the lowest energy of 22.4 GeV (figure 6) [7]. An additional dataset at $\sqrt{s_{\mathrm{NN}}}=$ 27 GeV with Au+Au has been taken in 2011 and will be analyzed soon. We conclude that the transition happens somewhere between the smaller Cu+Cu system at $\sqrt{s_{\mathrm{NN}}}=$ 22.4 GeV and Au+Au at $\sqrt{s_{\mathrm{NN}}}=$ 39 GeV.

4. Direct photon-tagged jets

In order to probe the energy loss in the medium, one can use direct photons to tag jets. The advantage of direct photons over a leading hadron is that the photon itself is not subject to energy loss in the medium. This gives a clean measurement

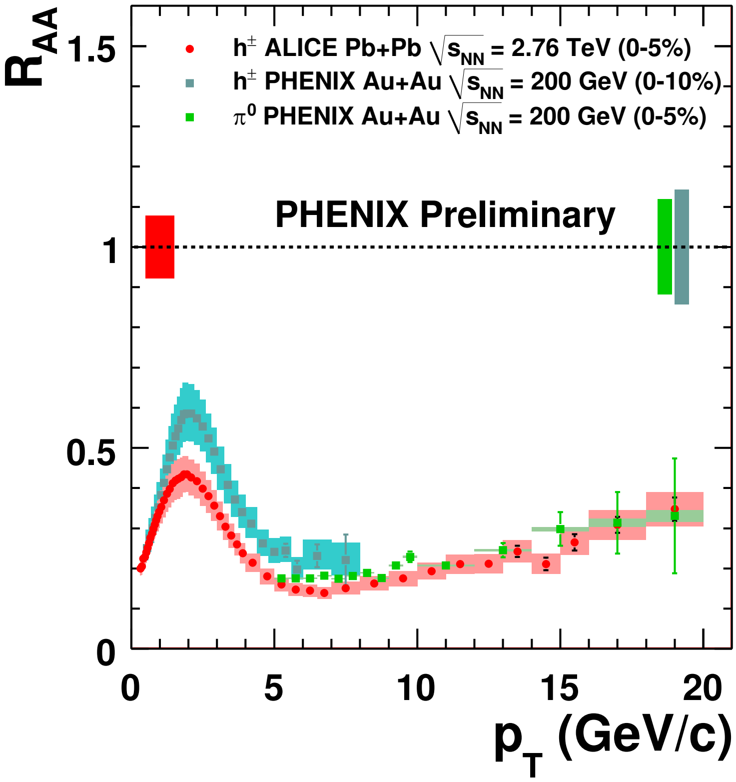

Figure 3. The nuclear modification factor of π^0 and charged hadrons as a function of p_T at $\sqrt{s_{\rm NN}}$= 200 GeV, overlaid with the data from ALICE at $\sqrt{s_{\rm NN}}$= 2.76 TeV.

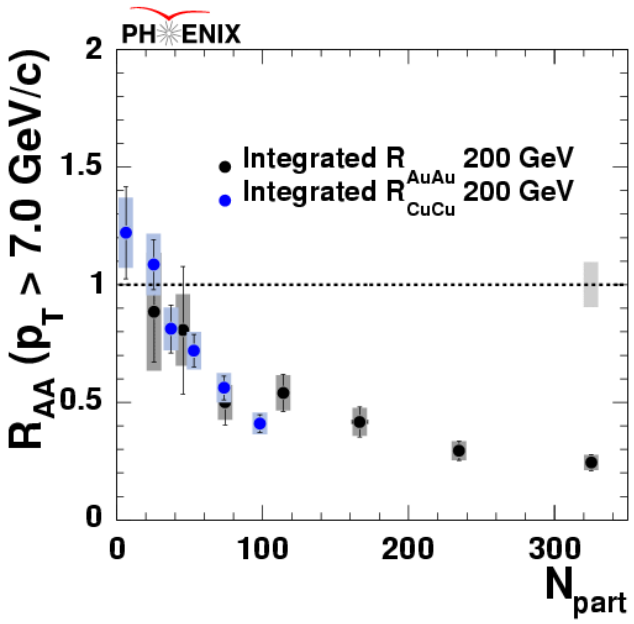

Figure 4. The nuclear modification factor of π^0 as a function of the number of participants $N_{\rm part}$ at $\sqrt{s_{\rm NN}}$= 200 GeV for Au+Au and Cu+Cu.

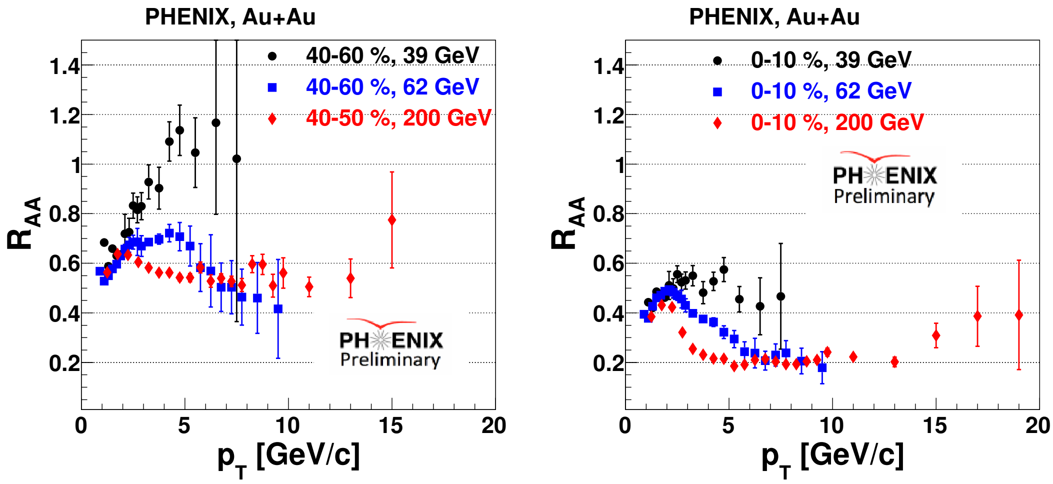

Figure 5. The nuclear modification factor of π^0 as a function of p_T from Au+Au collisions at different energies. The left figure is for a medium peripheral centrality range (40-60% for 39 and 62 GeV, and 40-50% for 200 GeV), and the right figure is for the most central collisions.

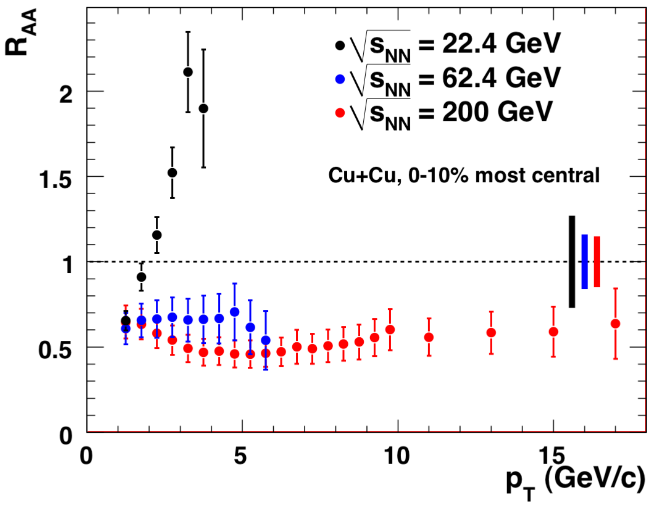

Figure 6. The nuclear modification factor of π^0 as a function of p_T from Cu+Cu collisions at different energies. While the curves from 62.4 and 200 GeV exhibit hadron suppression, the 22.4 GeV point is the only central data set so far to exhibit the enhancement.

of the total jet energy. This allows us to measure the jet fragmentation function by measuring the p_T of the leading particle in the jet, and calculating the fragmentation variables $x_E = p_T^h \cos(\Delta\phi)/p_T^{\mathrm{trigger}}$, and $\xi = -\ln(x_E)$. Figure 7 shows the ξ distribution for both p+p and Au+Au, and a theoretical prediction from the Modified Leading Logarithmic Approximation (MLLA) in the medium [8]. MLLA predicts an energy loss of the leading particle resulting in an increase in soft particle production, that is, an enhancement at high values of ξ, which we observe in the data. In order to expand the

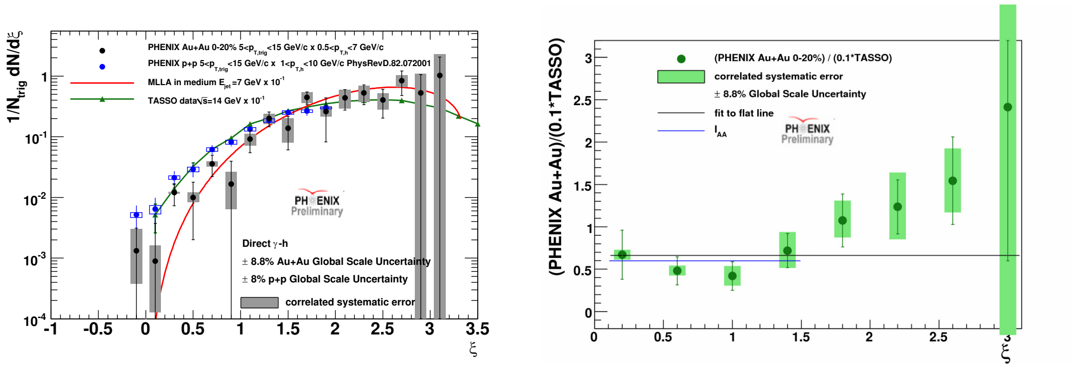

Figure 7. Left: The ξ distribution for PHENIX Au+Au (black circles) and p + p data (open blue circles), compared to a MLLA prediction (red line) and TASSO data (green triangles). Right: The ratio of PHENIX Au+Au data and the TASSO p+p data, which show a softening of the fragmentation function

reach of the p+p reference, we used the e^+e^- jet results from TASSO [9], scaled to account for the different acceptances. Figure 7 shows that the Au + Au distribution is shifted to higher ξ values as compared to p+p, which constitutes one of the first direct measurements of a fragmentation function in Au+Au collisions. It also allows to test full jet reconstruction algorithms for our data, and provides guidance for developing jet reconstruction capabilities in future detector upgrades.

5. The nuclear modification factor of fully reconstructed jets

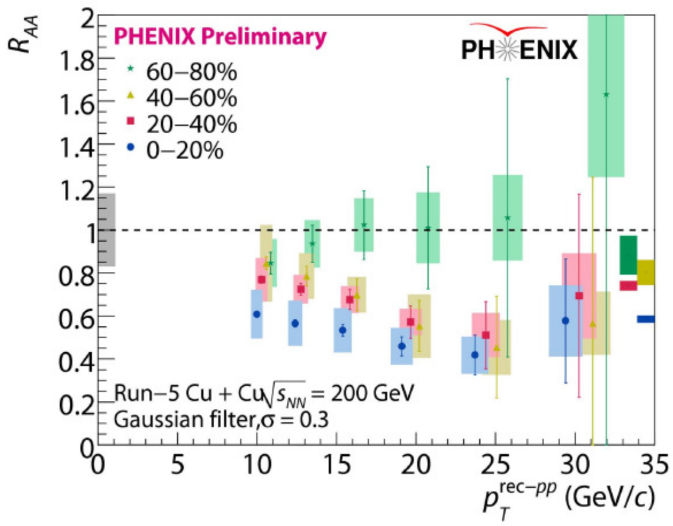

Figure 8. The nuclear modification factor of reconstructed jets as a function of p_T from Cu+Cu collisions at $\sqrt{s_{\rm NN}}=200\,$GeV. The shaded box to the left indicates the systematic uncertainty in the jet energy scale. The shaded boxes associated with data points indicate point-to-point systematic uncertainties, and error bars indicate statistical uncertainties.

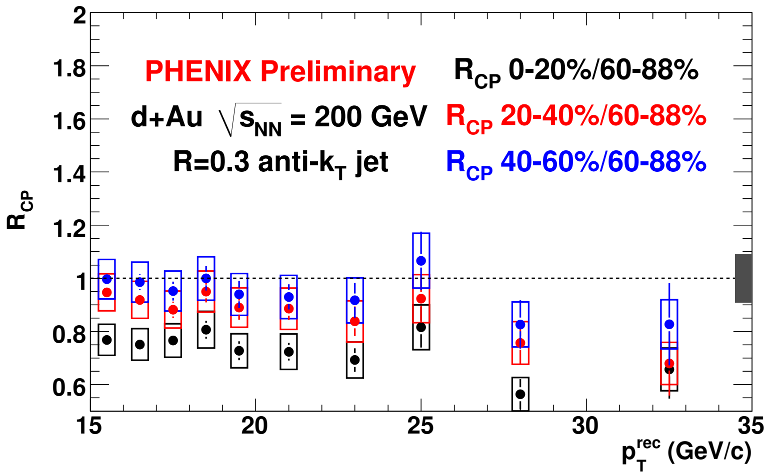

Figure 9. $R_{\rm cp}$ of reconstructed jets as a function of p_T from d+Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV. The jets in this figure were reconstructed with an anti-k_T algorithm with $R = 0.3$.

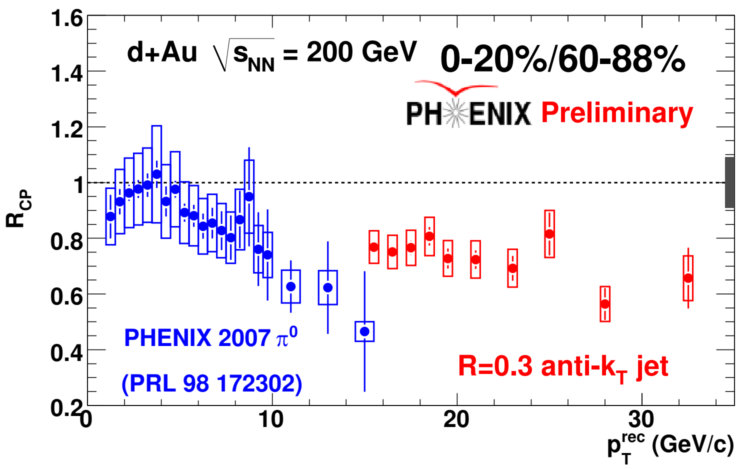

Figure 10. $R_{\rm cp}$ of reconstructed jets as a function of p_T from d+Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV, plotted together with π^0 data. The π^0 $R_{\rm cp}$ values are essentially the ratio of the top left distribution in Figure 2 and the fourth left panel.

Another way to probe the energy loss in the medium is to measure the nuclear modification factor of fully reconstructed jets. The analysis has been performed for Cu+Cu collisions at $\sqrt{s_{\rm NN}}$= 200 GeV [10]. Figure 8 shows jet $R_{\rm AA}$ (σ = 0.3 Gaussian filter) as a function of p_T in a p_T range up to 35 GeV/c. For the highest available centrality bin 0–20%, we observe a jet suppression similar to the suppression of neutral pions. The cause for the jet suppression could be out-of-cone radiation from medium interaction, or the jet shape could be modified in a way that is gets rejected (or some combination of both). For an in-depth discussion of the algorithms used, see [10].

In addition, the investigation of cold nuclear matter (CNM) effects is under way. At this point, we cannot yet present $R_{\rm dAu}$ for fully reconstructed jets, but have preliminary $R_{\rm cp}$ results, the ratio of central to peripheral data (Figure 9). The $R_{\rm cp}$ data indicate a level of CNM effects for jets which are of the same magnitude as for π^0, as shown in Figure 10. This is discussed further in [11].

6. Summary

We presented the nuclear modification factor R_{AA} for a number of measurements. We showed new results with higher statistics from neutral pion suppression in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$=200 GeV, and presented the participant scaling for Au+Au and Cu+Cu systems. The available results from the RHIC energy place the transition from an SPS-style hadron enhancement to suppression between the most central collisions at $\sqrt{s_{\mathrm{NN}}}$= 22.4 GeV in Cu+Cu and $\sqrt{s_{\mathrm{NN}}}$= 39 GeV for Au+Au.

We have analyzed direct photon-tagged jets to study the jet fragmentation function in p+p and Au+Au. We find that the fragmentation function shifts toward larger values of ξ. That measurement, together with the R_{AA} from fully reconstructed jets, will allow us to probe the energy loss scenarios in hot nuclear matter.

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